IDENTIFICATION, ASSOCIATION AND ANALYSIS OF RAYLEIGH WAVES IN THE CONTEXT OF CTBT MONITORING

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ABSTRACT

The correct identification and association of Rayleigh waves is vital within the context of the CTBT because of the use of the body-wave to surface wave magnitude ratio $m_b : M_S$ as a discrimination method. Rayleigh waves can be identified by their dispersion characteristics (the variation in group speed with frequency) and their elliptical polarization in the plane of propagation. Classically, Rayleigh waves are associated with a seismic disturbance by calculating the angle from which the wave arrives at a recording station (the 'back-azimuth'). Recently, two approaches to the detection of Rayleigh waves have been proposed (North and Woodgold, 1994; Chael, 1997) which rely on Rayleigh wave dispersion and polarization characteristics respectively.

Currently, the identification of Rayleigh waves at the IDC relies on software developed using the methodology of North and Woodgold (1994) and the group speed model of Stevens and McLaughlin (1996). The REB records the arrival time (and residual from the model), an amplitude measurement and consequent calculated M_S. Back-azimuths are also measured and recorded in the REB, although these are not used in associating a Rayleigh wave with a given seismic disturbance.

I present an analysis of Rayleigh wave detections in the REB for 1999 that shows that there is a very wide residual distribution for both arrival times and back-azimuths. For back-azimuths, only 55% of measurements lie within 30° of the great circle path. I also show that the accuracy of back-azimuth measurement varies at each station in the Primary IMS network, which may be a function of station locations, station noise levels and possible mis-orientation of horizontal components. There are a number of reasons why measured back-azimuths may vary from the great-circle between source and receiver. Earth structure can cause such deviations, but these are unlikely to be more than 30°. It may be that a Rayleigh wave associated with a different seismic disturbance has been selected in error, or it may be that the data is simply too noisy to make an accurate measurement. Finally, the processing of the data and the measurement technique applied may be sub-optimal.

In order to investigate the reasons for the large errors in back-azimuth seen in the REB I analyse data from a selection of events from January, 1999. The results of this analysis show that the large majority of back-azimuths, from a range of earthquake magnitudes and epicentre-station distances, can be measured to within 30° of the great-circle path. In those instances where such accuracy cannot be achieved, it is doubtful that the correct Rayleigh wave has been identified. For about 10% of paths, (including all the reports from one seismic disturbance) I can detect no Rayleigh wave at all despite the presence of an M_S measurement in the REB. This is potentially of grave consequence if $m_b : M_S$ is to be used as a discriminant between earthquakes and explosions.

Key Words: Rayleigh waves, Back-azimuth, M_S.

OBJECTIVE

To assess the analysis by the International Data Centre (IDC) of Rayleigh waves observed at seismic stations of the International Monitoring System (IMS) and to determine whether the levels of identification and association achieved can be improved upon.

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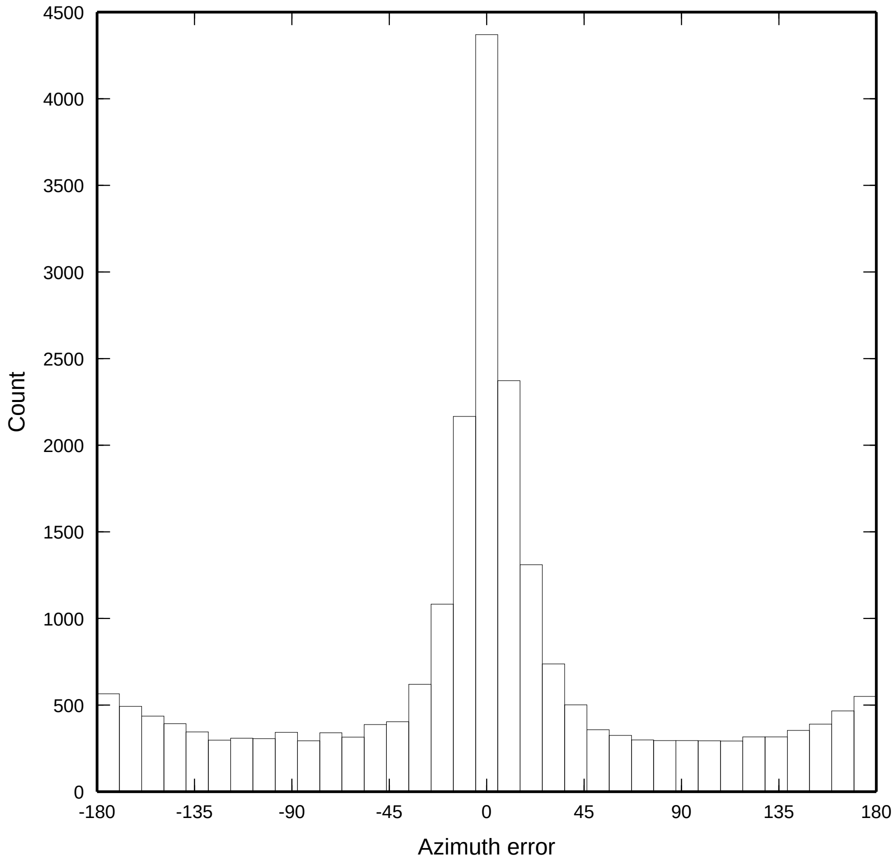

Figure 1: Distribution of back-azimuth residuals for Rayleigh wave observations in the REB 1 January 1999 - 25 November 1999.

RESEARCH ACCOMPLISHED

A brief perusal of the Reviewed Event Bulletin (REB) produced until February 2000 by the prototype International Data Centre (pIDC), Arlington, Virginia, USA and since that date by the IDC in Vienna, Austria, shows that the observations of Rayleigh wave (LR) phases often have large back-azimuth and arrival time residuals. Users of the REB may be drawn to the conclusion that observations with these large residuals should be treated with caution. It is important that all observations of LR in the REB can be relied upon, since the value of M_S, obtained from the measurement of Rayleigh wave amplitude, is used in an important screening criterion, the body-wave/surface-wave magnitude ratio, $m_b : M_S$. This study investigates the reliability of both the identification and association of Rayleigh waves in the REB. Here I use the term 'identification' to mean the detection of a Rayleigh particle motion and the term 'association' to mean the connection of an identified Rayleigh wave with a known epicentre, established using body-wave measurements.

Review of REB LR reports

To investigate the reliability of the back-azimuth measurements given in the REB I collated all LR reports for the period 1 January 1999 - 25 November 1999. Fig. 1 shows the distribution of the reported azimuth residual for the 22 934 observations. Approximately 45% of the residuals are greater than 30°. Earth structure can cause Rayleigh waves to deviate from the great-circle path (see, for example; Woodhouse and Wong, 1986; Laske, 1995; Bungum and Capon, 1974) but I believe that ±30° is a generous margin which should encompass the back-azimuth of all first arriving wave-packets at the frequencies and path

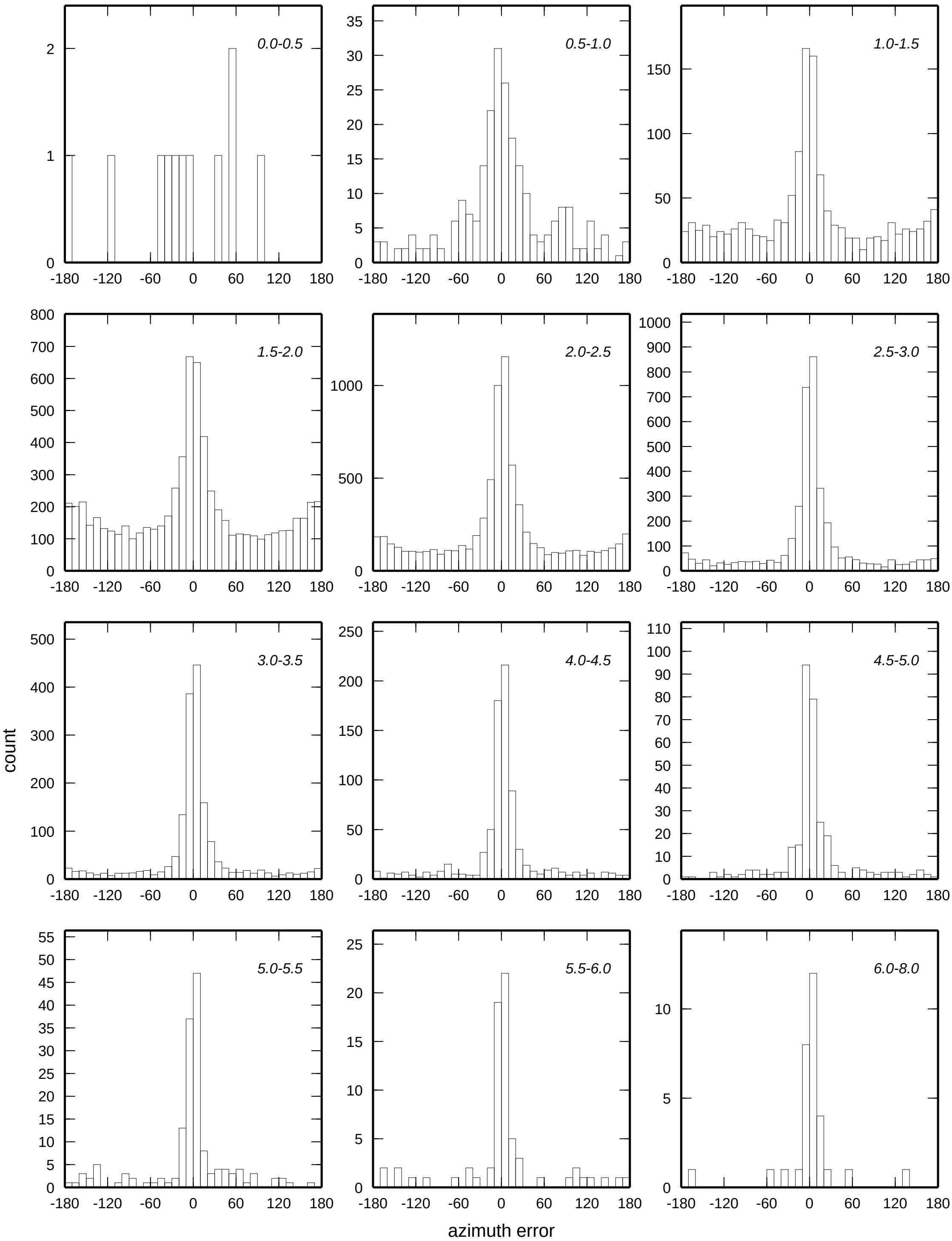

Figure 2: Azimuth error plotted against log (measured amplitude)

Station	Error	Station	Error	Station	Error	Station	Error
ARCES	+15	CMAR	+5	MAW	-10	PLCA	0
BDFB	-5	DBIC	-20	MNV	+20	SCHQ	0
BGCA	-10	ESDC	0	NOA	0	ULM	0
BJT	+5	HIA	0	NRIS	T	YKA	-5
BOSA	0	ILAR	+20	PDAR	+5	ZAL	T
BRAR	-15	KSAR	0	PDY	T		

Table 1: Stations used in this study and systematic error at each station. T=triaxial seismometer.

Event no.	Date	Time	Location	Lat	Long	Ms	LR
20276833	1999/01/01	09:05:46	SUDAN	4.33N	31.41E	3.5	4
20277798	1999/01/02	17:55:04	SICHUAN, CHINA	27.29N	101.12E	3.9	8
20279693	1999/01/04	11:09:57	SE SIBERIA	57.45N	123.63E	3.2	3
20281441	1999/01/05	18:27:41	ETHIOPIA	6.23N	37.62E	3.6	4
20288809	1999/01/13	04:36:19	VENEZUELA	9.99N	63.83W	3.8	2
20291674	1999/01/14	22:45:15	NW CAUCASUS	41.10N	44.00E	4.2	13
20291760	1999/01/15	10:16:35	CRETE	34.65N	26.37E	3.3	4
20291801	1999/01/15	13:45:57	IRAN-IRAQ	35.47N	45.25E	3.1	2
20293318	1999/01/17	19:32:13	ITALY	39.09N	17.33E	4.2	12
20299300	1999/01/22	02:36:23	SE SIBERIA	57.24N	120.60E	3.3	1
20300510	1999/01/22	22:48:01	SUDAN	5.06N	32.31E	3.4	4
20304734	1999/01/25	18:19:15	COLOMBIA	4.41N	75.56W	5.7	11
20307458	1999/01/27	19:07:54	LAKE BAYKAL	55.92N	110.52E	2.8	2
20307707	1999/01/27	21:24:28	CHILE	40.48S	72.15W	4.2	3
20309281	1999/01/28	22:28:11	ZAMBIA	15.76S	26.42E	3.4	2
20310643	1999/01/29	18:42:32	CALIFORNIA	28.10N	112.08W	3.8	10
20313853	1999/01/31	08:16:01	E CAUCASUS	43.05N	46.96E	3.5	7
20314536	1999/02/01	04:52:41	S. ZEMLYA	85.51N	86.45E	4.6	12

Table 2: Earthquakes used in this study. Event number in the pIDC REB catalogue, Date, Time, Location, Latitude, Longitude, Surface wave magnitude (Ms), number of associated Rayleigh waves (LR).

lengths under investigation. Consequently we must assume that the back-azimuth residuals of these 45% must be due to one of four causes: mis-alignment of the horizontal components at a station; measurement of a mis-associated or mis-identified Rayleigh wave; a poor application of the measurement technique; or it may be that back-azimuth measurement to within the accuracy required is not possible.

Figure 2 shows the distribution of back-azimuth error partitioned by the logarithm of the measured Rayleigh amplitude reported in the REB. Note that the vertical scale is different in each panel. It is clear that at high amplitudes back-azimuths are measured accurately, as would be expected since these measurements will have a high signal-to-noise ratio. However, the poorest distribution is not at the lowest amplitudes. A possible explanation for this is that small amplitude Rayleigh waves cannot be detected at the noisiest stations and so are not reported.

Investigation of systematic station residuals

Wang and Stead (1998) carried out an analysis of back-azimuth residuals for body-wave phases recorded at three-component stations. Elsewhere (Selby, 1999), I have carried out an analysis of each station which listed LR observations during the study period. In Fig. 3 I show examples of the back-azimuth residual distribution at four stations. The character of this distribution is different at each station. HIA, which appears to be one of the most reliable IMS stations for LR detection and association has a narrow peak centred on zero (i.e. the great-circle back-azimuth). CMAR has a broader central peak which is also

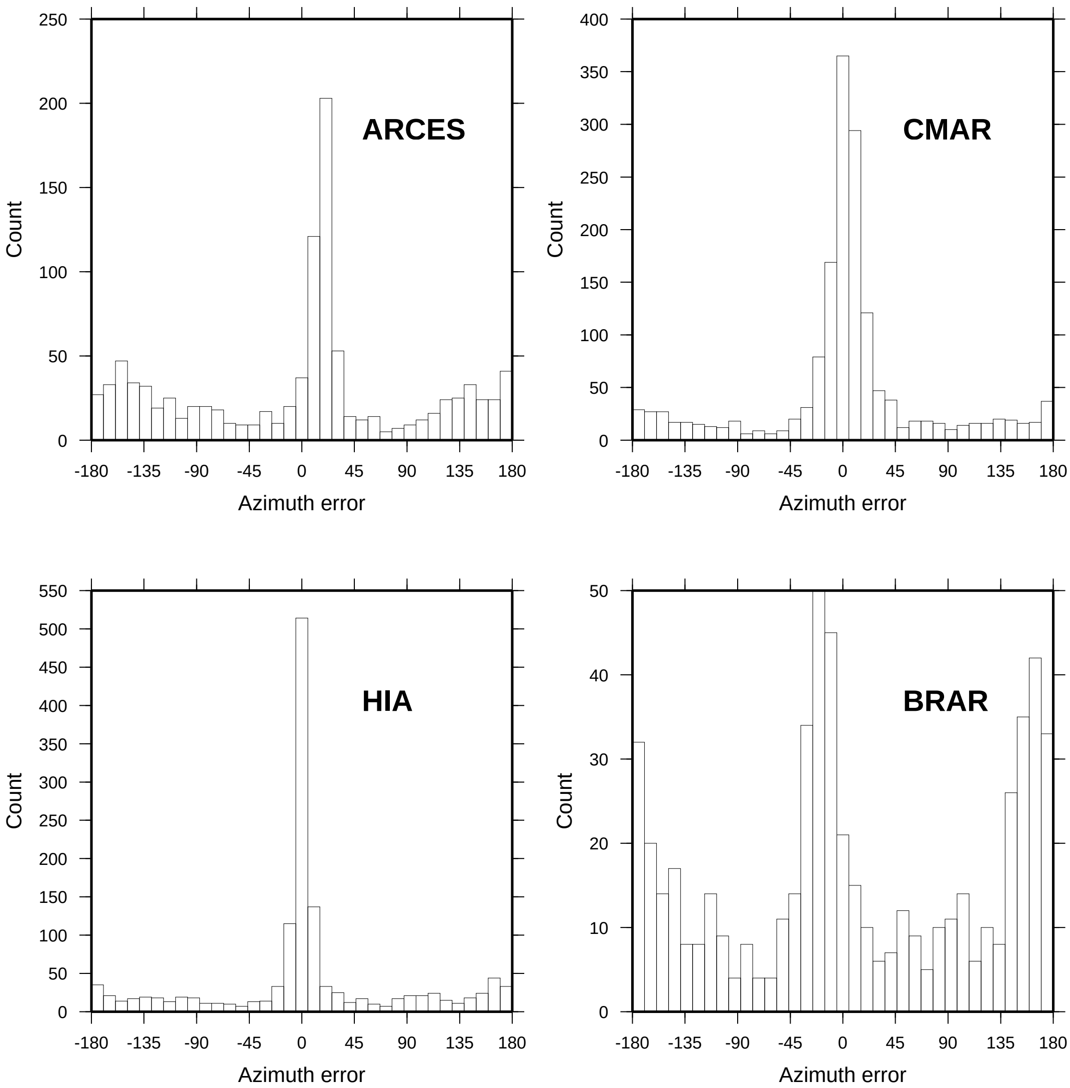

Figure 3: Back-azimuth residual distributions for IMS stations ARCES (1037 measurements), CMAR (1598 measurements), HIA (1371 measurements) and BRAR (576 measurements)

centred on zero. ARCES shows a higher level of background, random residuals and its central peak is offset from zero. At BRAR, although there are fewer observations, the distribution of residuals is uneven and shows two major peaks. Because the pattern of residual distribution is so different at every station it is rather hard to decide on the cause of systematic errors. Some stations show large peaks which are simply offset from zero, perhaps suggesting a simple misalignment of horizontal components, whereas at other stations there may be more complex problems. Because it is not known whether these errors are due to station misalignment or to other factors (such as structure at the station) and also because the error distributions are not normal, I choose not to make a fully accurate measurement of this systematic error. In my view each station should be checked for mis-alignment rather than assumptions made based on averaging of remote data. Re-enforcing this view is the fact that the findings of Wang and Stead (1998), based on body-wave data, do not always agree with my results. However, the errors estimated do perhaps indicate which stations require investigation. The stations NRIS, PDY and ZAL in Russia are triaxial (rather than conventional three component). Assessment of pIDC REB back-azimuth reports from these stations show that there is no straight-forward relationship between observed and predicted azimuth at these stations. Wang and Stead (1998) explain how these distributions are related to the alignment of the

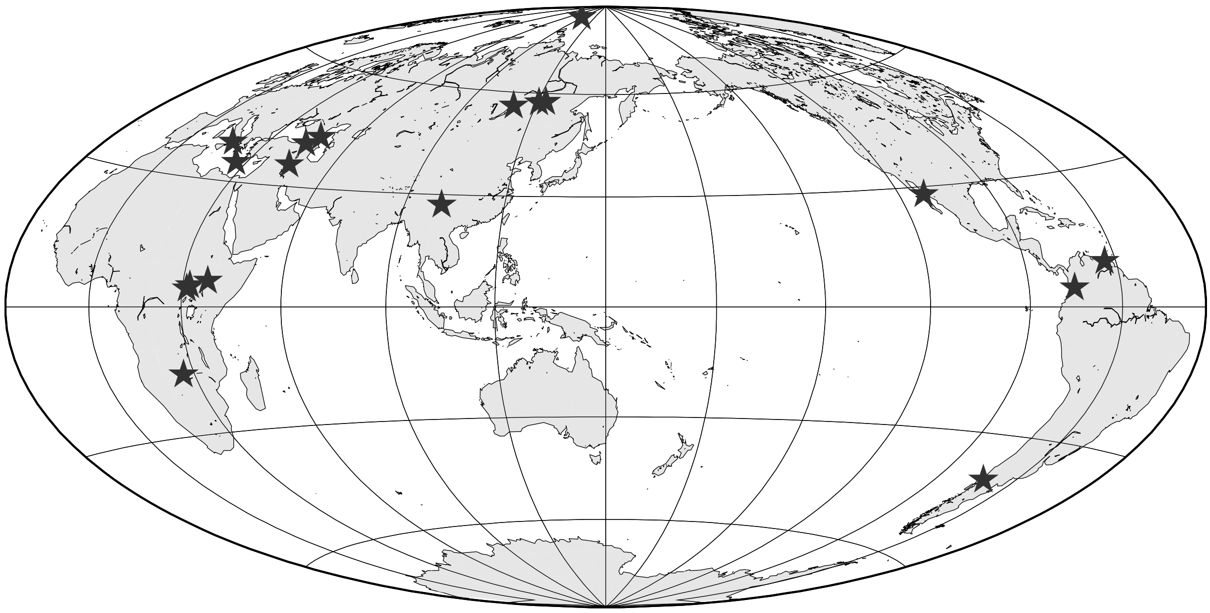

Figure 4: Distribution of events used in this study

triaxial components, but since I are not concerned here with the orientation of station components I proceed no further with these stations. In table 1 I show the approximate systematic error observed at each station.

Analysis of a selection of waveforms

In order to determine the sources of error in the REB LR back-azimuth reports I analyze data from a selection of earthquakes from 1 January 1999 - 1 February 1999. 18 earthquakes with 105 associated LR reports were selected. Table 2 lists the selected earthquakes, their locations and the number of IMS stations reporting LR. The location of these earthquakes is shown in Fig. 4. The earthquakes were chosen to have epicentres on shore or close to the continental edge, to be shallow (REB depth 0km) and cover a range of magnitudes. Data were acquired for each path for a time window starting at the origin time of the earthquake and ending 30 minutes or one hour later, depending on the epicentre-station distance. A multiple taper dispersion plot (Dziewonski *et al.*, 1969; Dziewonski and Hales, 1972) is produced for the vertical component and from this time and frequency windows are selected. The back-azimuth is calculated from the cross-correlation of the Hilbert transformed vertical and radial components (see, for example, Chael, 1997). Elsewhere (Selby, 2000) the analysis of these data is described in more detail. Fig. 5 shows a comparison of measured back-azimuth and geometric (great-circle) back-azimuth for paths for which I was able to make a measurement. The dotted lines show the $\pm 30°$ error bounds. The grey squares are the pIDC

Case	N	%
Back-azimuth measured to within 30°	74	70.5
Back-azimuth measured, error greater than 30°	2	1.9
No Rayleigh wave found	8	7.6
Rayleigh wave on vertical component only	2	1.9
Data incomplete or faulty	8	7.6
Data not retrieved	4	3.8
Triaxial, not processed	7	6.7

Table 3: Summary of the results of this study

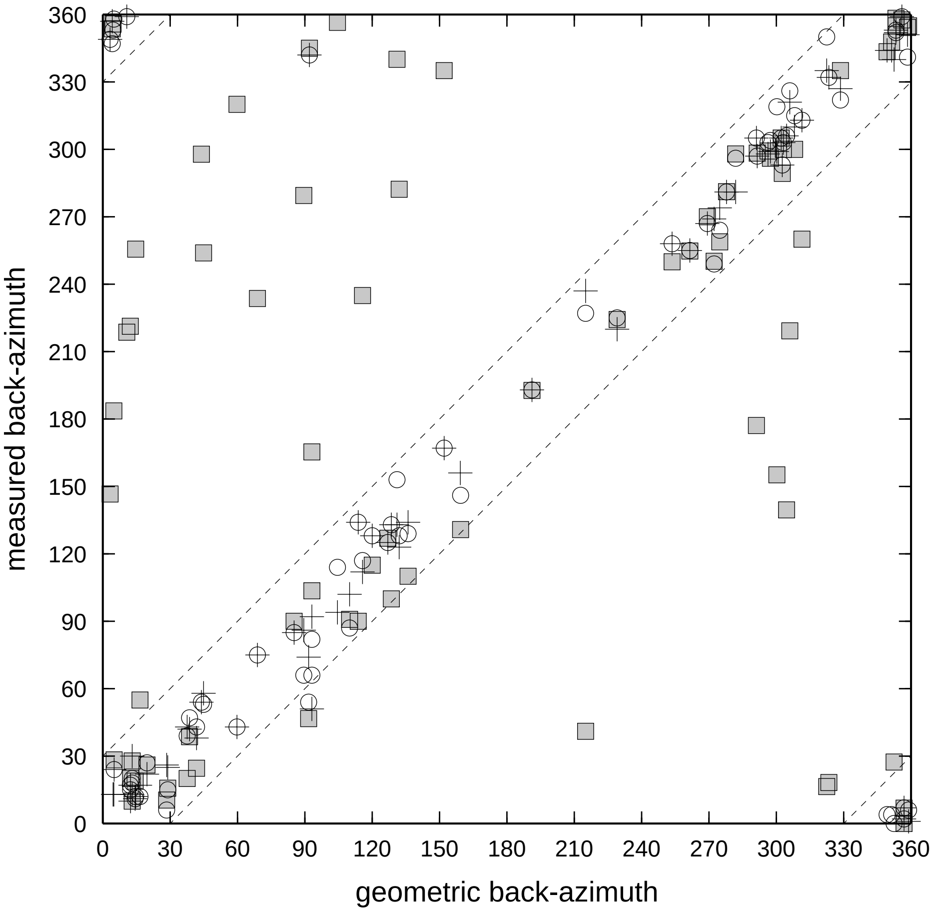

Figure 5: Observed back-azimuth plotted against geometric back-azimuth. Filled squares: PIDC measurements. Open circles: this study. Crosses: This study plus correction for station systematic error.

measurements given in the REB. There is a large scatter. Open circles show the measurements made in this study and the crosses these measurements adjusted using the station systematic errors in Table 1. It is clear that for the large majority of paths included in this study it is possible to make sufficiently accurate back-azimuth measurements to associate an observed Rayleigh wave with the epicentre. In Fig. 5 only two measurements lie outside the 30° error bounds. On further inspection (Selby, 2000) these turn out not to be the correct waveforms. Fig. 5 shows clearly that the systematic station errors discussed earlier do not form a major part of the back-azimuth residuals observed. It also shows that where a Rayleigh wave has been identified correctly it has also been associated correctly. Hence the large azimuth residuals must be due to poor processing of the data or a poor measurement technique.

CONCLUSIONS AND RECOMMENDATIONS

Table 3 shows the final results of the waveform analysis. Of the 105 waveforms for which the back-azimuth was measured, 74 gave an answer within ±30° of the great-circle back-azimuth. Only two gave an error greater than 30°, and further examination showed that these were unlikely to be correctly identified or associated Rayleigh waves. More worrying is that for 8 paths I was unable to detect a Rayleigh wave at all. For a further two paths there may have been a suspicion of a Rayleigh wave on the vertical component only, but this is not certain. In particular, for one earthquake (REB event 20281441, Ethiopia, see Table 2) I was unable to detect any Rayleigh waves at all, suggesting that the REB quoted M_s for this earthquake is meaningless. I found no examples of genuine Rayleigh waves associated with the wrong event, which

indicates that the global model used by the pIDC (Stevens and McLaughlin 1996, 1997) is effective as a dispersion test. However, measurement of noise to give a surface wave magnitude is clearly undesirable. Any automated routine used for verification must only identify and associate definite Rayleigh waves. It seems clear from this study that a dispersion test alone cannot do this if the signal-to-noise ratio is low, sometimes, M_s may be measured from noise rather than the correct Rayleigh wave. It is of course difficult to design an automated routine which can achieve the same reliability as analyst review, but any algorithm must only find and measure Rayleigh waves where an analyst would see them. In these circumstances it seems that a routine must include the following elements

- a dispersion test
- a test for degree of polarization
- a back-azimuth measurement
- a signal-to-noise ratio test.

The algorithm should be able to select a time window and frequency band for which the signal-to-noise ratio is good, which shows the correct dispersion, is correctly polarized and has the right back-azimuth.

To conclude, polarization and back-azimuth measurements can be made to within the desired accuracy for Rayleigh waves at periods useful to verification. If a back-azimuth estimate cannot be made with a high level of coherence or if the azimuth is incorrect, then there must be doubt about whether the correct waveform has been identified and it should not be used to measure surface wave magnitude.

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